STEM ESSENTIALS

Efficacy of Plant-Based Natural Coagulants for Domestic and Industrial Water Purification

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Abstract

Water purification remains a pressing concern globally, particularly in regions with limited access to clean water. Chemical coagulants, while effective, often pose environmental and health challenges. This review explores the viability of plant-based natural coagulants (PNCs) as sustainable, efficient, and eco-friendly alternatives for domestic and industrial water purification. Drawing from empirical research and case studies, we examine various plant sources, coagulation mechanisms, treatment efficiency, influencing factors, and scalability. The findings reveal that PNCs hold significant promise for enhancing water treatment, especially in resource-constrained communities.

KEYWORDS: Water Purification, Coagulants, Plant-based Natural Coagulants, Water Treatment

Introduction

Access to clean and safe water is a fundamental human right and a cornerstone of public health, economic development, and environmental sustainability. However, many regions, especially in developing countries, struggle to meet this basic need. Conventional water treatment methods have relied heavily on inorganic chemical coagulants for decades. While effective in removing turbidity and pathogens, these chemicals have raised significant concerns. Issues such as chemical residuals, high sludge volumes, cost implications, and potential links to neurological disorders from prolonged exposure have prompted researchers and practitioners to seek alternatives.

Water treatment processes play a crucial role in ensuring public health and environmental protection. Traditional water treatment methods primarily rely on synthetic coagulants such as aluminum sulfate (alum), ferric chloride, and polyaluminum chloride, which are effective but come with drawbacks, including high operational costs, sludge disposal problems, and potential health risks due to residual metal ions (Ndabigengesere et al., 1995). In response to these concerns, natural coagulants derived from plants have garnered increasing attention as viable alternatives. Plant-based natural coagulants (PNCs) offer several benefits: they are biodegradable, locally available, cost-effective, and often generate less sludge.

Plant-based natural coagulants (PNCs) present a promising solution. Derived from seeds, leaves, bark, and roots of various plants, PNCs possess bioactive compounds capable of destabilizing suspended particles and facilitating floc formation. Their appeal lies in biodegradability, low toxicity, local availability, and cost-effectiveness. More importantly, they align with global sustainability goals, particularly in water-stressed and low-income communities where modern treatment infrastructure is lacking. This review investigates their performance, comparing them to conventional coagulants, analyzing the biochemical mechanisms behind their coagulation activity, and discussing their application in domestic and industrial water treatment contexts.

Fundamentals of Water Coagulation

The coagulation process is essential in water treatment, serving as the initial step for removing suspended solids, colloids, and pathogens. The mechanism by which PNCs operate is primarily rooted in the presence of functional groups such as proteins, polysaccharides, and polyphenols. These biomolecules act through several pathways: charge neutralization, adsorption, inter-particle bridging, and sweep flocculation. Charge neutralization occurs when positively charged molecules in plant extracts bind to the negatively charged surfaces of colloidal particles, thereby reducing the electrostatic repulsion between them. For instance, the seed extract of Moringa oleifera is rich in low molecular weight cationic proteins that effectively neutralize charges and facilitate aggregation. Adsorption and inter-particle bridging involve larger biomolecules like polysaccharides creating physical connections between particles, forming flocs that can be easily separated by sedimentation or filtration.

The efficiency of coagulation is influenced by multiple factors, including the type and concentration of the coagulant, pH, temperature, mixing speed and duration, and the nature of the water being treated. PNCs are known to perform optimally in neutral to slightly acidic conditions. Turbidity removal efficiencies often range between 70% and 99%, depending on the source water and treatment protocol. Microbial reduction is another important performance parameter. Some plant coagulants possess intrinsic antimicrobial properties. Moringa oleifera, for example, has been shown to reduce bacterial loads of E. coli and Salmonella significantly, suggesting a dual function in both coagulation and disinfection. Other PNCs, like those derived from Strychnos potatorum and Hibiscus sabdariffa, have demonstrated varying degrees of antimicrobial activity.

Coagulation Mechanism

Coagulation involves the destabilization of colloidal particles in water, typically negatively charged, to facilitate their aggregation into larger flocs for subsequent removal. Conventional coagulants neutralize charges via metal ions, while PNCs work through adsorption, bridging, or charge neutralization using bioactive compounds such as proteins and polysaccharides (Yin, 2010).

Key Parameters

Efficiency in coagulation is influenced by parameters including pH, temperature, dosage, mixing time, and turbidity levels. Plant-based coagulants exhibit varying performance based on these factors, emphasizing the need for tailored application strategies (Ali et al., 2010).

Prominent Plant-Based Natural Coagulants

Among the vast number of plants studied for coagulation properties, a few have garnered significant attention due to their efficacy and availability. Moringa oleifera is arguably the most researched PNC. Native to the Indian subcontinent and widely cultivated in tropical regions, its seeds contain water-soluble proteins with strong coagulating potential. Moringa-based treatment systems have been implemented at both household and community levels in countries like India, Sudan, and Ethiopia. Studies report turbidity reductions of up to 99%, with additional benefits such as low sludge volume and minimal secondary pollution.

i Moringa oleifera: One of the most extensively researched PNCs, Moringa seeds contain cationic proteins (6-16 kDa) that serve as excellent flocculating agents. Studies have shown high turbidity removal (up to 99%) in surface water with Moringa extracts (Ndabigengesere & Narasiah, 1996). Its application spans from household to community-scale systems in Africa and Asia.

ii Cicer arietinum (Chickpea): Chickpea extract is rich in proteins and polysaccharides, showing promising coagulation properties. Ali et al. (2010) reported turbidity reductions of 90% in synthetic water samples, with optimal performance at pH 6-7.

iii Hibiscus sabdariffa: The calyx extract of Hibiscus sabdariffa contains anthocyanins and organic acids that contribute to coagulation efficiency. It demonstrates potential in wastewater treatment, particularly in dye and heavy metal removal (Okuda et al., 2001).

iv Opuntia spp. (Cactus): Cactus mucilage is composed of polysaccharides with coagulating properties. Jar tests have shown effective turbidity removal from both synthetic and industrial effluents, with pH tolerance from 4 to 9 (Diaz et al., 1999).

v Strychnos potatorum: Native to India, this plant's seeds have long been used in traditional water purification. The active agents are polysaccharides and alkaloids, which coagulate impurities effectively in slightly alkaline conditions (Ghebremichael et al., 2005).

Coagulation Efficiency and Water Quality Improvement

i *Turbidity Reduction*: Most PNCs achieve 80–99% turbidity removal, comparable to alum under optimized conditions (Okuda et al., 2001). Efficiency is higher in waters with higher initial turbidity, due to greater particle interaction.

ii *Pathogen Reduction:* Several studies have shown PNCs to reduce microbial load due to antimicrobial compounds in seeds and leaves (Bhuptawat et al., 2007). For instance, Moringa shows bactericidal activity against *E. coli* and *Salmonella spp.*

iii *Heavy Metal and Dye Removal*: Plant extracts with chelating agents can remove heavy metals like lead and cadmium, and organic compounds including dyes from textile wastewater (Yin, 2010). Hibiscus and cactus extracts are notably effective.

Application in Domestic and Industrial Settings

The scalability of PNCs in water treatment remains a significant hurdle. While laboratory and pilot-scale studies show promise, few have transitioned into large-scale, consistently managed treatment systems. This is partly due to the challenges in maintaining consistent quality and dosage control in plant-based coagulants. Developing standardized protocols and automated dosing systems could address these concerns.

i *Domestic Water Purification*: PNCs are suitable for decentralized water treatment in rural and peri-urban areas. Moringa and chickpea extracts can be integrated into simple filtration systems. Studies in India and Ethiopia have validated their effectiveness in household-scale use (Ghebremichael et al., 2006).

ii *Industrial Wastewater Treatment*: Textile, tannery, and food processing industries have explored PNCs as part of integrated treatment systems. For example, Opuntia has been used to treat tannery effluent with over 70% COD reduction (Diaz et al., 1999). However, scalability and consistency remain challenges.

Factors Affecting Performance

i pH Sensitivity: Most PNCs function optimally in neutral to slightly acidic pH ranges. Extreme pH can denature the bioactive compounds, reducing coagulation potential (Ali et al., 2010).

ii Temperature: High temperatures may enhance extraction but reduce shelf-life and stability of coagulant solutions. Cactus mucilage, however, shows resilience to temperature variations (Diaz et al., 1999).

iii Storage and Shelf Life: A significant limitation is the short shelf life of crude plant extracts. Drying and powdered formulations of Moringa and chickpea have been proposed to improve shelf life and facilitate transport (Ndabigengesere & Narasiah, 1996).

Comparison with Conventional Coagulants

i Cost Efficiency: PNCs are often locally sourced and inexpensive. Cost-benefit analyses in Ghana and Kenya showed that Moringa-based treatment systems can be up to 60% cheaper than alum-based systems in small communities (Ghebremichael et al., 2006).

ii Environmental Impact: Unlike chemical coagulants, PNCs produce biodegradable sludge with lower aluminum or iron residues, reducing ecological harm and disposal concerns (Yin, 2010).

iii Health Considerations: Alum residues are associated with Alzheimer's disease and other neurological risks. PNCs, being biodegradable and natural, are safer for human consumption, though toxicological studies are still necessary for less-studied plants (Bhuptawat et al., 2007).

Limitations and Research Gaps

Despite their promise, PNCs face challenges:

- **Standardization**: Variability in plant species, growth conditions, and extraction methods affects performance.
- **Scalability**: Industrial-scale production is limited by supply chain and formulation issues.
- **Toxicology**: Insufficient data on long-term exposure and metabolite effects.
- **Regulation**: Lack of regulatory frameworks governing PNC use in public water systems.

Future research should address these limitations through multi-site field trials, biochemical characterization, and pilot-scale implementation projects.

Future Prospects and Innovations

Emerging trends include:

- **Nano-enhanced PNCs**: Combining plant extracts with nanoparticles for improved flocculation and antimicrobial action.
- **Bio-composite Filters**: Integration of PNCs into ceramic or polymer matrices for slow-release coagulation.

- **Machine Learning Models**: To optimize dosage and predict coagulation performance under different water conditions.

Investment in local research capacity and public-private partnerships will be key to mainstreaming these technologies in low-resource settings.

Conclusion

Plant-based natural coagulants offer a compelling alternative to synthetic chemicals for water purification, with applications ranging from rural domestic systems to industrial wastewater treatment. Their environmental safety, cost-effectiveness, and local availability make them especially relevant for developing regions. While challenges remain, particularly in standardization and large-scale deployment, continued research and innovation can unlock their full potential. A paradigm shift towards natural water treatment agents can play a pivotal role in achieving global water security and sustainability.

References

- Ali, E. N., Muyibi, S. A., Salleh, H. M., Salleh, M. R. M., & Kait, C. F. (2010). Moringa oleifera seeds as natural coagulant for water treatment. *Water Resources and Industry*, 1, 45–50.
- Bhuptawat, H., Folkard, G. K., & Chaudhari, S. (2007). Innovative physicochemical treatment of wastewater incorporating Moringa oleifera seed coagulant. *Journal of Hazardous Materials*, 142(1-2), 477–482.
- Diaz, A., Rincon, N., Escorihuela, A., Fernandez, N., Chacin, E., & Forster, C. F. (1999). A preliminary evaluation of turbidity removal by natural coagulants indigenous to Venezuela. *Process Biochemistry*, 35(3-4), 391–395.

- Ghebremichael, K. A., Gunaratna, K. R., Henriksson, H., Brumer, H., & Dalhammar, G. (2005). A simple purification and activity assay of the coagulant protein from Moringa oleifera seed. *Water Research*, 39(11), 2338–2344.
- Ghebremichael, K. A., et al. (2006). Production and characterization of water treatment coagulants from Moringa oleifera seed. *Water Supply*, 6(1), 21–30.
- Ndabigengesere, A., & Narasiah, K. S. (1996). Quality of water treated by coagulation using Moringa oleifera seeds. *Water Research*, 32(3), 781–791.
- Okuda, T., Baes, A. U., Nishijima, W., & Okada, M. (2001). Isolation and characterization of coagulant extracted from Moringa oleifera seed by salt solution. *Water Research*, 35(2), 405–410.
- Yin, C. Y. (2010). Emerging usage of plant-based coagulants for water and wastewater treatment. *Process Biochemistry*, 45(9), 1437–1444.